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13. ABSTRACT *(Maximum 200 words)*

The objective of this research is to develop, validate and evaluate novel semi-active and active-passive hybrid structures for real-time vibration suppressions. These types of structures normally require less power than the purely-active systems. Also, since energy is almost always being dissipated, they are more stable than the active approach. In other words, they have the advantages of both the passive (stable, low power requirement, fail-safe) and active (high performance, feedback actions) systems. In this research, the Penn State researchers investigated four types of adaptive structure configurations using electrorheological (ER) fluids and piezoelectric materials: ER dampers, semi-active piezoelectric networks, active-passive hybrid piezoelectric networks, and active constrained layer damping treatments. New actuator concepts have been created, and novel control/design methodologies have been developed. The results show that the semi-active and active-passive hybrid configurations are indeed very effective in controlling structural vibrations

14. SUBJECT TERMS semi-active vibration controls, active-passive hybrid vibration controls, adaptive structures, electrorheological fluids piezoelectric materials, active constrained layer damping, shunted piezoelectric circuits

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SEMI-ACTIVE VIBRATION CONTROLS OF FLEXIBLE STRUCTURES VIA ADAPTIVE MATERIALS

FINAL PROGRESS REPORT

K. W. WANG

JULY 20, 1996

U. S. ARMY RESEARCH OFFICE

GRANT NO. DAAH04-93-G-0065

THE PENNSYLVANIA STATE UNIVERSITY

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A. STATEMENT OF PROBLEM STUDIED

The objective of this research is to develop, validate and evaluate novel semi-active and active-passive hybrid adaptive structures for real-time vibration suppressions. These types of structures normally require less power than the fully-active systems. Also, since energy is almost always being dissipated, they are more stable than the active approach. In other words, they have the advantages of both the passive (stable, low power requirement, fail-safe) and active (high performance, feedback actions) systems. They will thus eliminate the concerns that people have with active devices, and yet still outperform the classical passive systems. The major research tasks include (a) actuator concept development, (b) actuator/structure modeling and characterization, (c) control law development and system integration, (d) control-configured adaptive structure design methodology development, and (e) experimental validations.

B. SUMMARY OF THE MOST IMPORTANT RESULTS

(1) The Penn State researchers have developed a comprehensive model and nonlinear control laws for semi-active electrorheological (ER) fluid dampers. It is found that both the pre-yield and post-yield conditions of the fluid have to be considered in the modeling process. Given periodic displacement inputs, the damper force is measured. When the pre-yield contribution is significant, Figure 1 demonstrates that the comprehensive model developed at Penn State can represent the experimental results much better than the classical Bingham model.

A nonlinear feedback control system is designed, based on the theory of Sliding Mode, for semi-active vibration suppressions through controlling the ER actuator viscous and frictional damping characteristics. A lab fixture is set up to evaluate the semi-active concept (Figure 2). The experimental hardware consists of a cantilever beam (6061-T6 aluminum, 635mm x 38.1mm x 6.35mm) with the ER damper connected at the tip. The control law is implemented through a TMS320-C25 DSP board with the necessary D/A and A/D boards (interfaced with a PC-386 machine). The output signal is obtained using two strain gages mounted to the beam in a half-bridge configuration. To provide the electric field necessary for activating the ER fluid, a Bertan 602B high voltage (0 to 10kV) power supply is used. Given an initial displacement of the beam tip, the time response of the structure is illustrated in Figure 3. When no electric field is applied, the system response will overshoot and oscillate before reaching the equilibrium. With maximum electric field, no overshoot will occur. However, the beam is not returning to its original configuration. This phenomenon, which is also predicted in the numerical simulation, is mainly caused by the significant frictional force of the actuator when high voltage is being applied. With the semi-active action, the test results show that the structure vibrations are damped out very effectively. That is, the system returns to its equilibrium configuration with fast decay rate and no overshoots.

With the validated model, the characteristics of the ER fluid damper are also incorporated in the design of an adaptive vibration absorber. Implementing the absorber on a vibrating structure, the main structure frequency response is shown in Figure 4. It can be observed that the system with the ER fluid vibration absorber outperforms (exhibits lower level of vibration through out a wide frequency range) systems with optimally tuned passive absorbers (damped and undamped). This illustrates that the adaptive properties of an ER fluid damper can be well utilized to provide superior performance and flexibility over a passive viscous damper.

(2) The Penn State researchers have developed adaptive structures with piezoelectric materials and *real-time-controlled* (significantly different from the past passive and quasi-static methods) *semi-active* electrical networks. An energy analysis is performed to identify the energy distributions of the actuators and structural components. Based on this analysis, a novel energy-based nonlinear scheme is synthesized for on-line vibration controls. With this control law, the total system energy (the main structure mechanical energy plus the electrical and mechanical energies of the piezoelectric material and electrical circuit) will always be reduced to ensure stability while energy of the main structure will be constrained to suppress vibration.

To evaluate the semi-active system performance, analysis is carried out on a beam structure (Figure 5). Given an impulse input, Figure 5 illustrates time response of the beam vibration.

Comparing to an uncontrolled (short circuit) case, the system's vibration suppression capability is much improved (faster decay rate of response) when the semi-active action is activated.

(3) The Penn State researchers have developed innovative piezo-based intelligent structures with *active-passive hybrid* electrical networks. The hybrid networks consist of the piezoelectric materials in series with an active voltage source and passive shunt circuits (Figure 6). A method is created to systematically and simultaneously optimize the active control gains and the values of the shunt resistor and inductor. It is shown that this active-passive approach can outperform the purely-passive system (more vibration reduction). It is also illustrated that the hybrid structure can achieve better vibration suppression performance while requiring less control effort when compared to a purely active system.

The controlled and uncontrolled (short circuit) cases are compared in Figure 7 (random excitation applied to structure), where the effectiveness of the active-passive controller is clearly demonstrated. To further investigate the merit of the hybrid system, we compare it against the purely active case (no passive circuit). It is shown that the active-passive design results in a better structure response (smaller standard deviation of vibration amplitude). A comparison of the required voltage for both the active-passive and purely active systems is also illustrated in Figure 7. From this figure, it is clear that the hybrid design not only achieves better vibration control performance compared to the active approach but also requires less effort (voltage).

(4) The Penn State researchers have developed *new* active constrained layer (ACL) treatments for active-passive hybrid structural controls. A current active constrained layer (ACL) system generally consists of a piece of passive viscoelastic damping materials (VEM) sandwiched between an active piezoelectric layer and the host structure. It has been shown that the ACL treatments can enhance the system damping when compared to a traditional passive constrained damping layer approach. However, when compared to a purely active case (zero VEM thickness), the ACL viscoelastic layer will reduce the direct control authorities from the active source to the host structure, due to the reduction of transmissibility.

In this research, the Penn State researchers first developed a thorough analysis to understand the contributions of the different actuator elements, which provides design guidelines for one to select the *correct* ACL and VEM parameters. With such guidelines, one could achieve a truly effective active-passive hybrid system that would outperform both the purely active and passive cases. Based on such understanding, the Penn State researchers further created a *new* active constrained layer configuration (Figure 8) to improve the active action transmissibility (control authority) of the current ACL treatment. Introducing an *edge element*, the active action from the piezoelectric cover sheet can be transmitted to the host structure more directly. On the other hand, such a configuration still has the damping ability of the passive VEM. In other words, it has the benefits of both the current ACL and a purely active system. Experimental results indicate that the new configuration has significantly more control authority (active action transmissibility) than the current ACL treatments (see Figure 9).

From our study, it is recognized that the new ACL can greatly enhance the active action transmissibility while retaining a similar level of passive damping ability, when compared to the current ACL. The major interest now is to study the overall system performance combining the active and passive actions. To investigate this, we define an index I_{ap} representing the vibration suppression ability per control effort, which indicates the effectiveness or efficiency of the active-passive hybrid actions.

The I_{ap} value versus κ (viscoelastic material parameter related to shear modulus) and α (viscoelastic material parameter related to loss factor) for the current and new ACLs is plotted in Figure 10. The purely active case (corresponding to a flat plain since no VEM is involved) is also plotted for the purpose of comparison. The region in which the I_{ap} value of the ACL is larger than that of the active system (flat plain) will give us a design that can outperform both the purely active and passive approaches. On the other hand, the region in which the ACL I_{ap} surface is lower than the flat plain (purely active results) is not desirable. Following this argument, we see that the current ACL system has a very limited VEM design space (Figure 10(a)). With the new edge elements, the I_{ap} value of the new ACL in the original undesirable VEM region in Figure 10(a) becomes greater than that of the purely active case (Figure 10(b)). In fact, the new ACL will outperform the active configuration in the complete κ - α range in Figure 10(b). Through broadening the VEM design space, we are now achieving a more robust design (performance is less sensitive to the viscoelastic material properties).

To illustrate the improvement of the new ACL over the current ACL, examples of a beam impulse response are illustrated in Figure 11. With the given VEM material and ACL configuration, it is shown that the current ACL treatment requires more control effort while achieving less vibration reduction when compared to a purely active system. By adding the edge elements, the new ACL not only can outperform the current ACL significantly (more vibration reduction with less control effort), but also shows improvement over the purely active system.

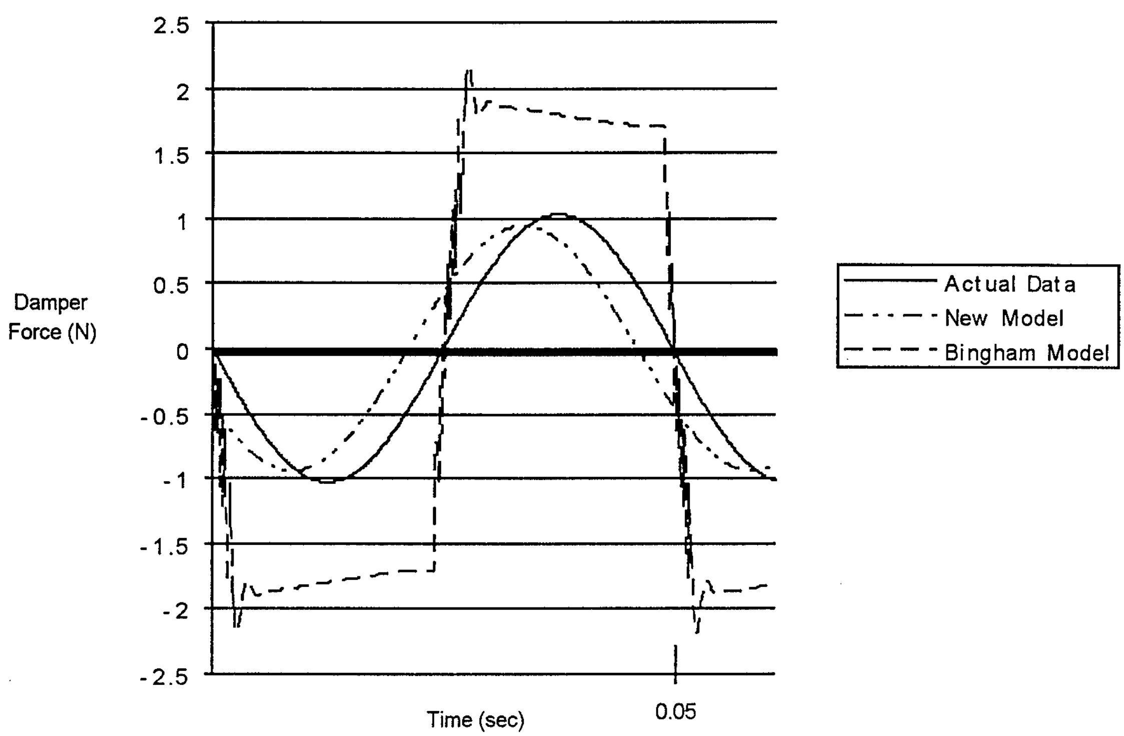
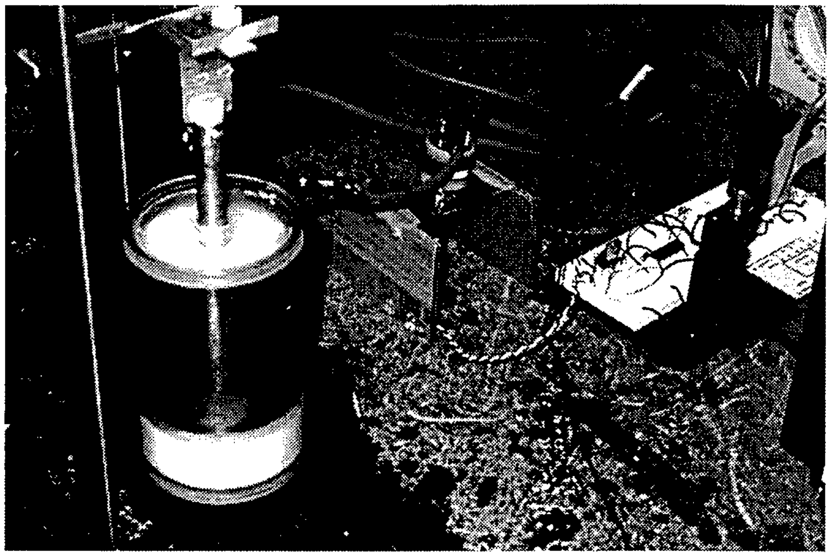


Figure 1. **Results comparing damping force of the new model, the classical Bingham model, and the experimental data of an ER damper.**



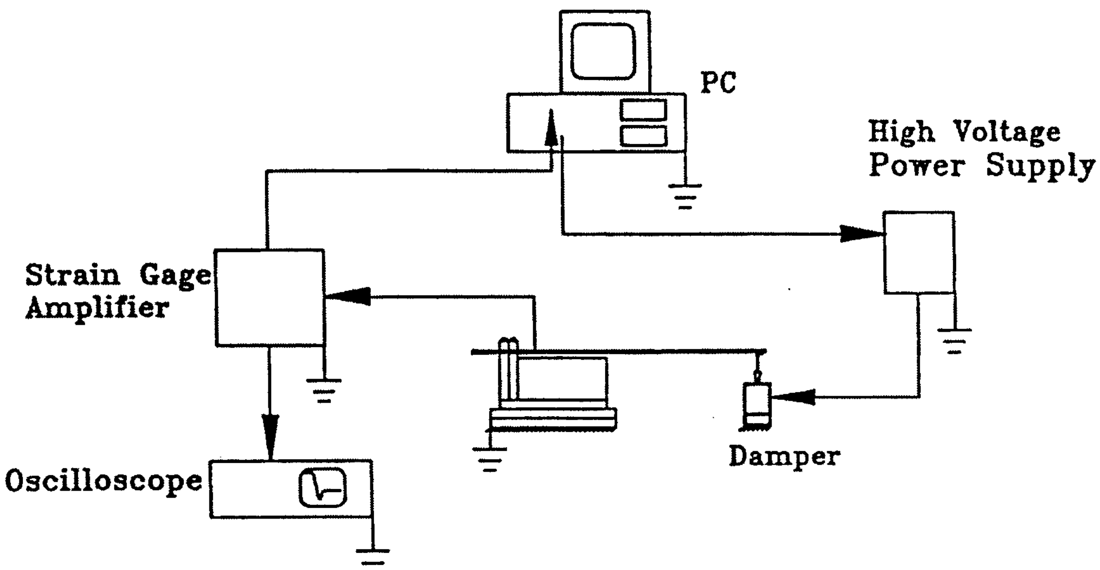


Figure 2. Upper: an ER damper. Lower: schematic of the ER damper control experimental set up.

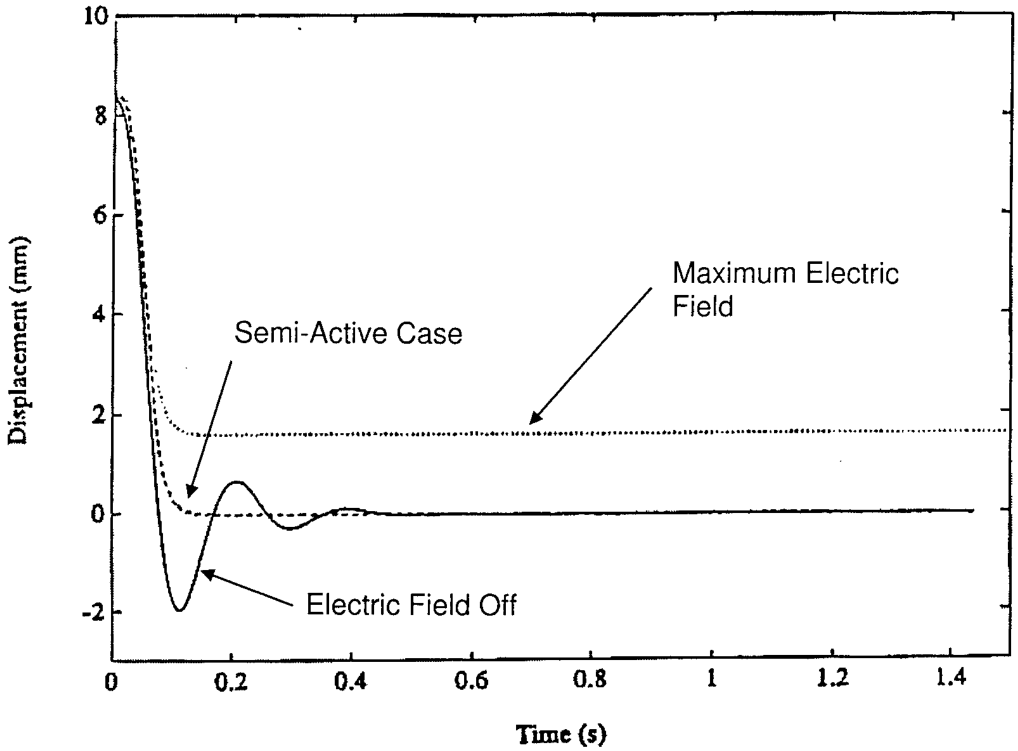


Figure 3. Experimental results : time response of the beam structure with ER damper.

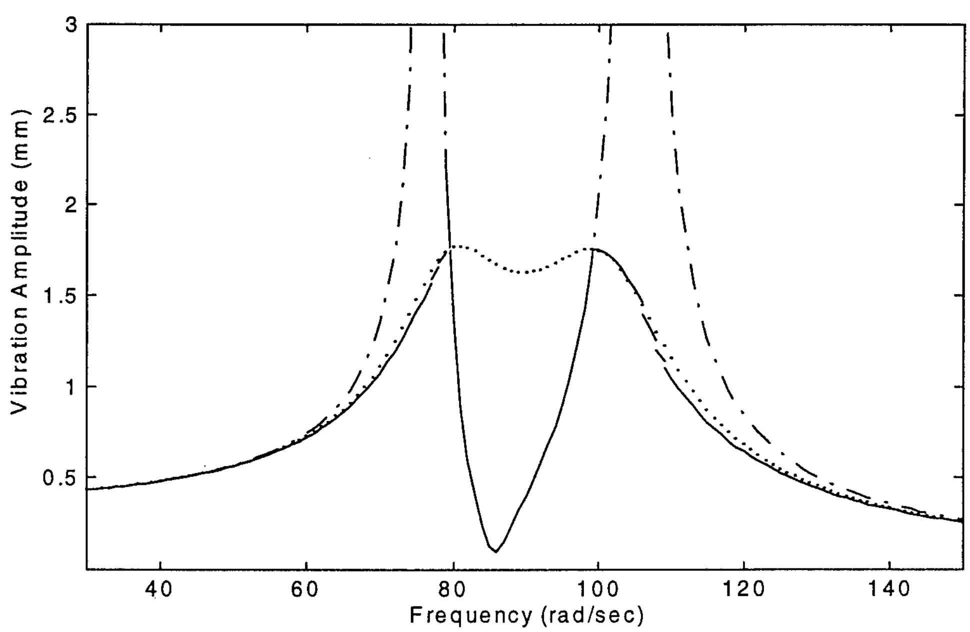
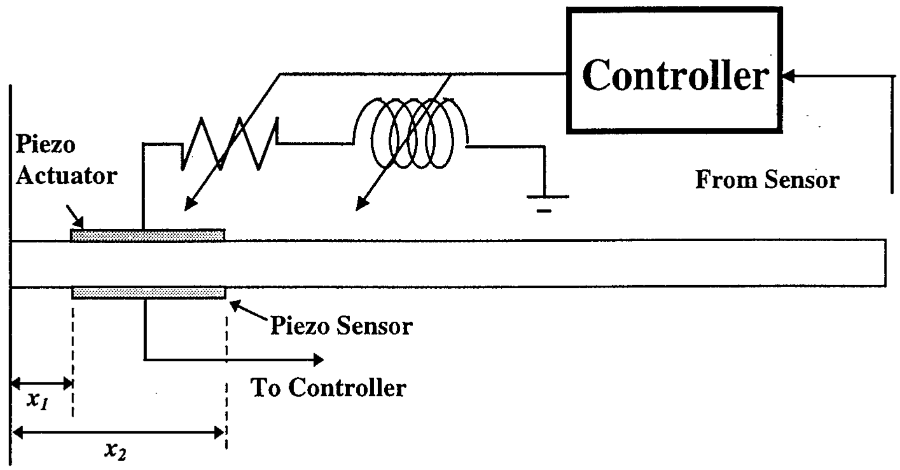


Figure 4. Vibration amplitude of the main structure vs. forcing frequency. Comparing the ER-based adaptive absorber case (solid line) with the optimally tuned passive absorbers (damped: dotted line, undamped: dashed line)



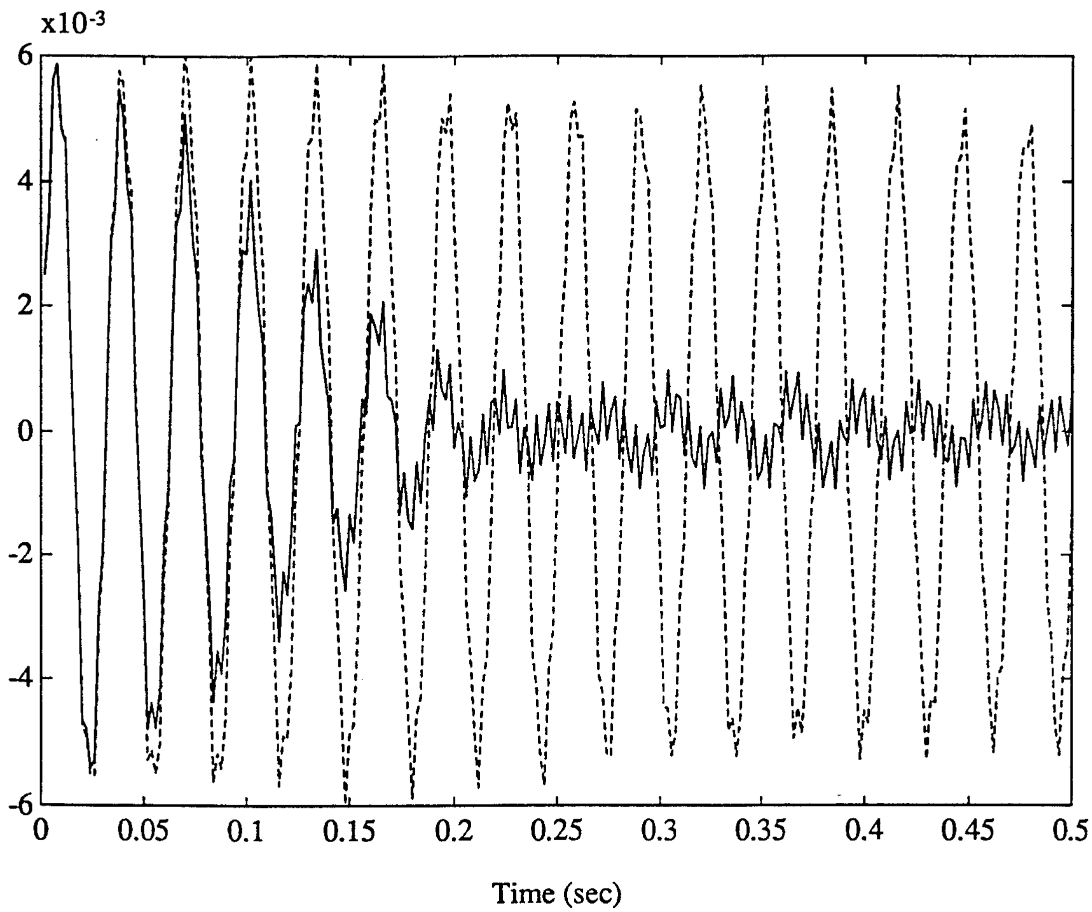


Figure 5. **Upper: schematic of a cantilever beam with semi-active piezoelectric circuit. Lower: beam tip vibration impulse response. Solid line: semi-active case. Dashed line: passive case with short circuit.**

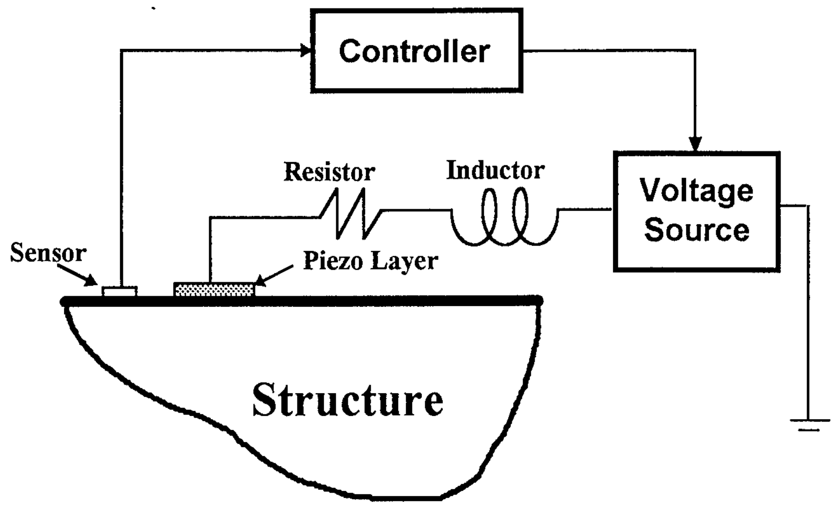


Figure 6. Adaptive structure with active-passive hybrid piezoelectric networks

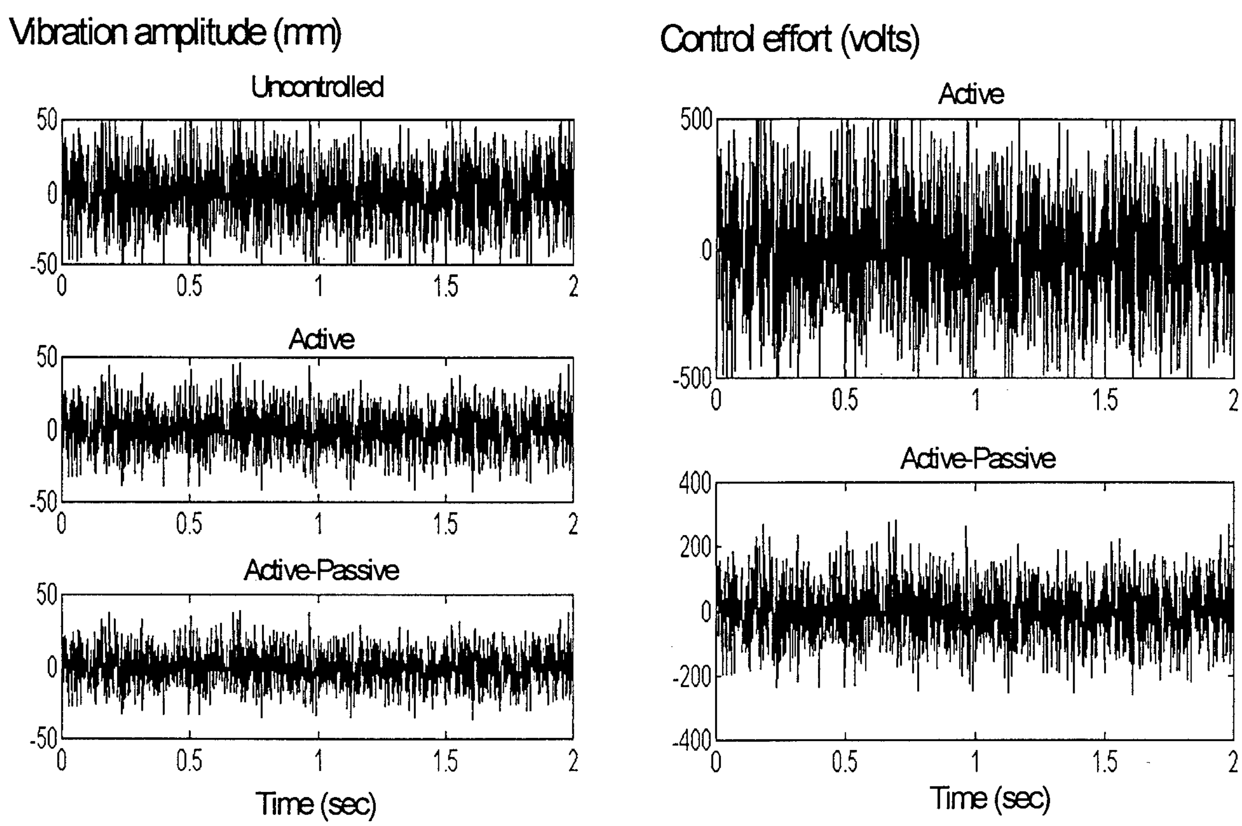


Figure 7. Left plots: structure response random sequence (upper plot: no control, middle plot: purely active, lower plot: active-passive). Right plots: control effort random sequence (upper plot: purely active, lower plot: active-passive).

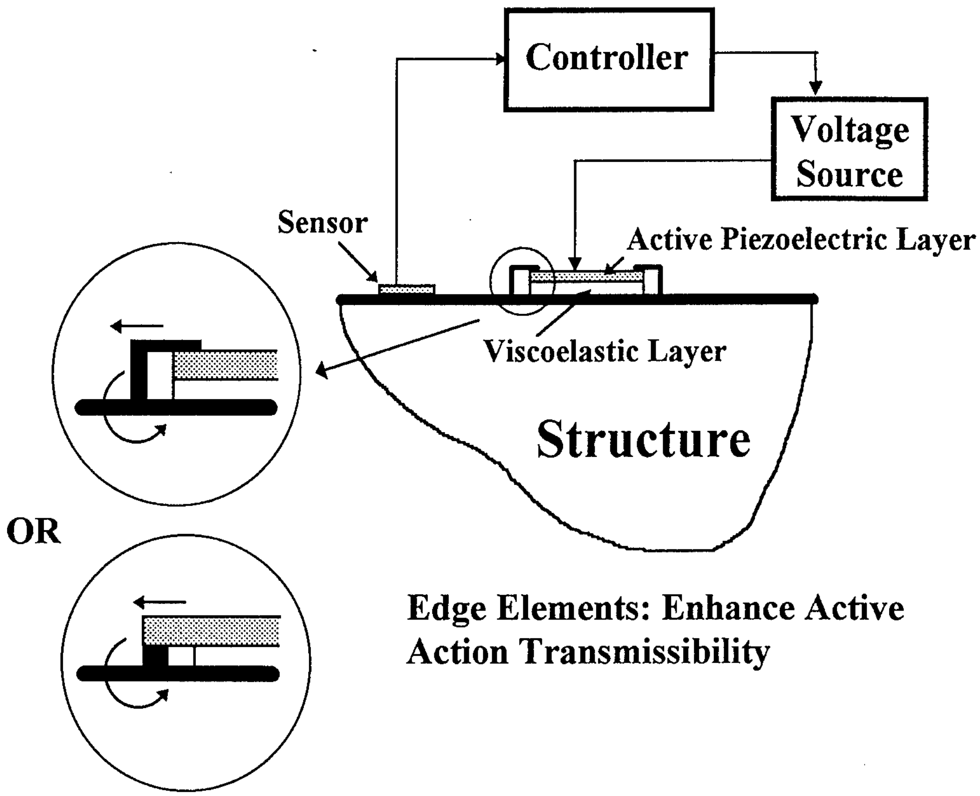


Figure 8. New ACL configuration with edge elements to enhance active action transmissibility.

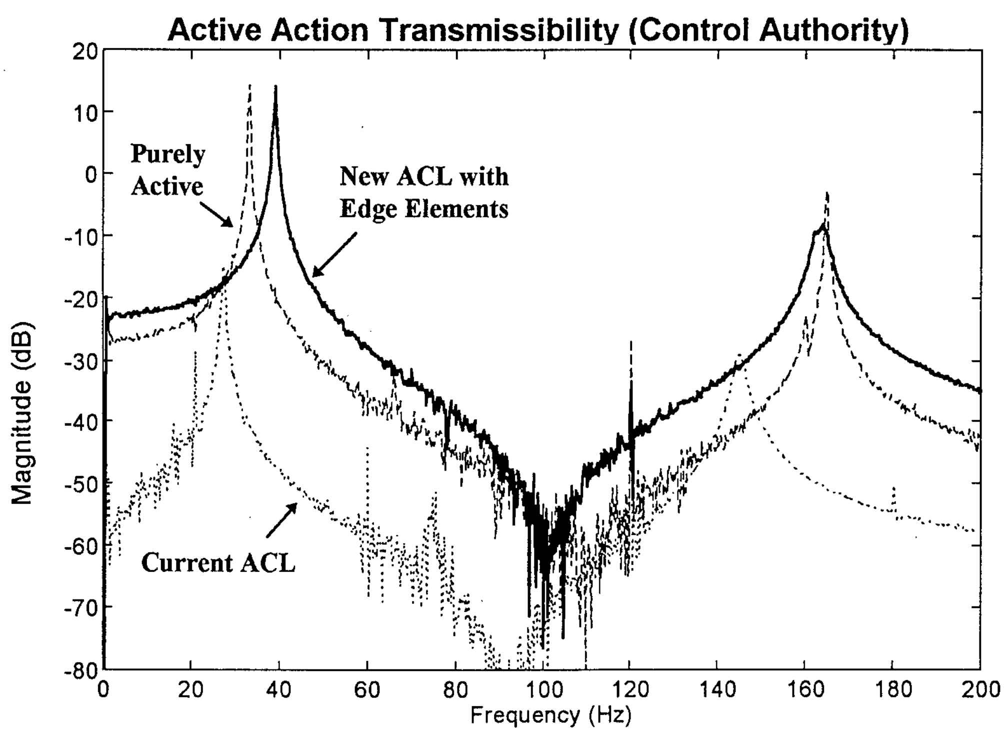


Figure 9. Experimental results illustrating active action transmissibility (control authority) of the various actuators. It is shown that the new ACL outperforms both the current ACL and the purely active configuration.

Hybrid Control Index (Vibration Reduction / Control Effort) vs. VEM parameters

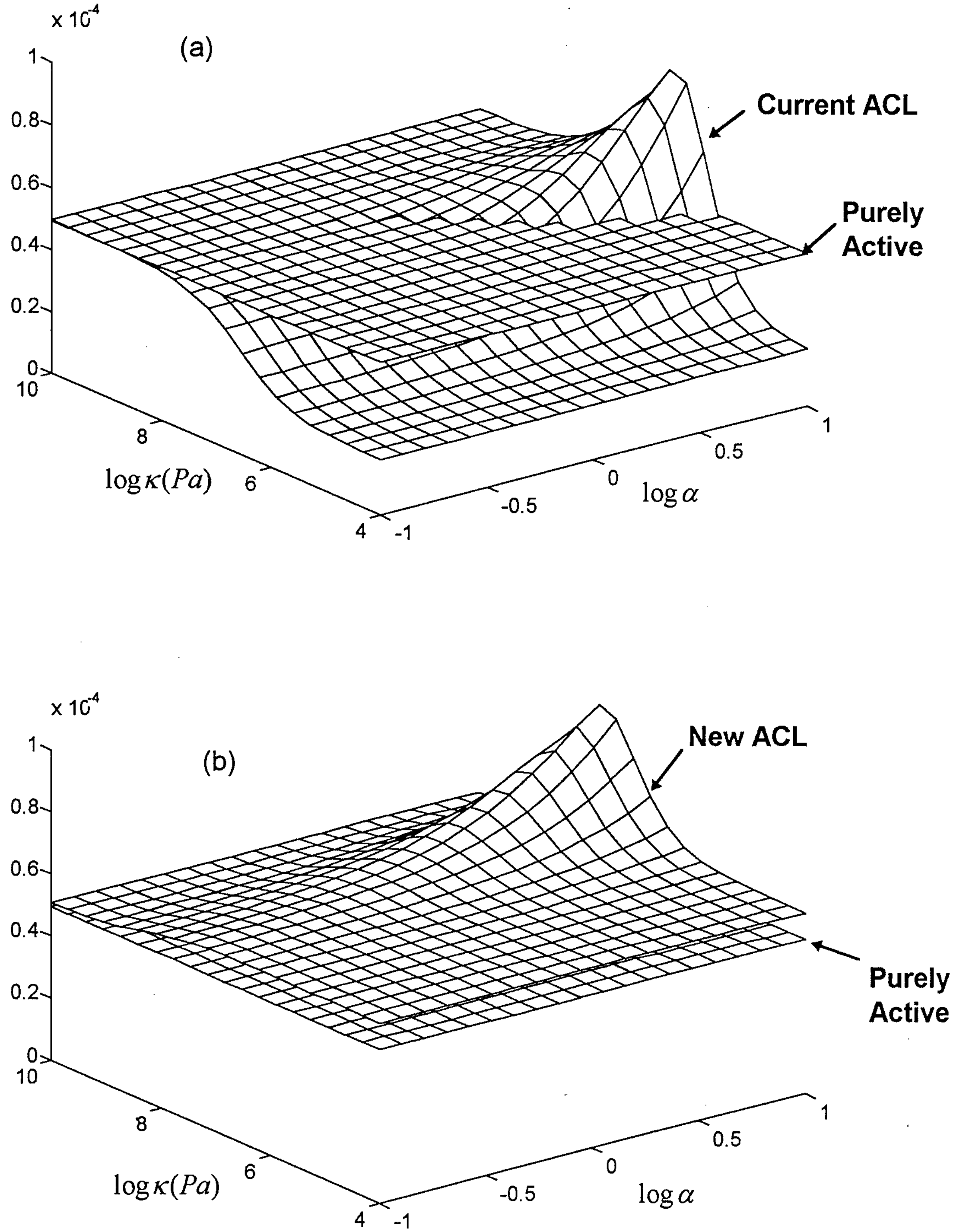


Figure 10. Index I_{ap} versus κ and α for current ACL and New ACL

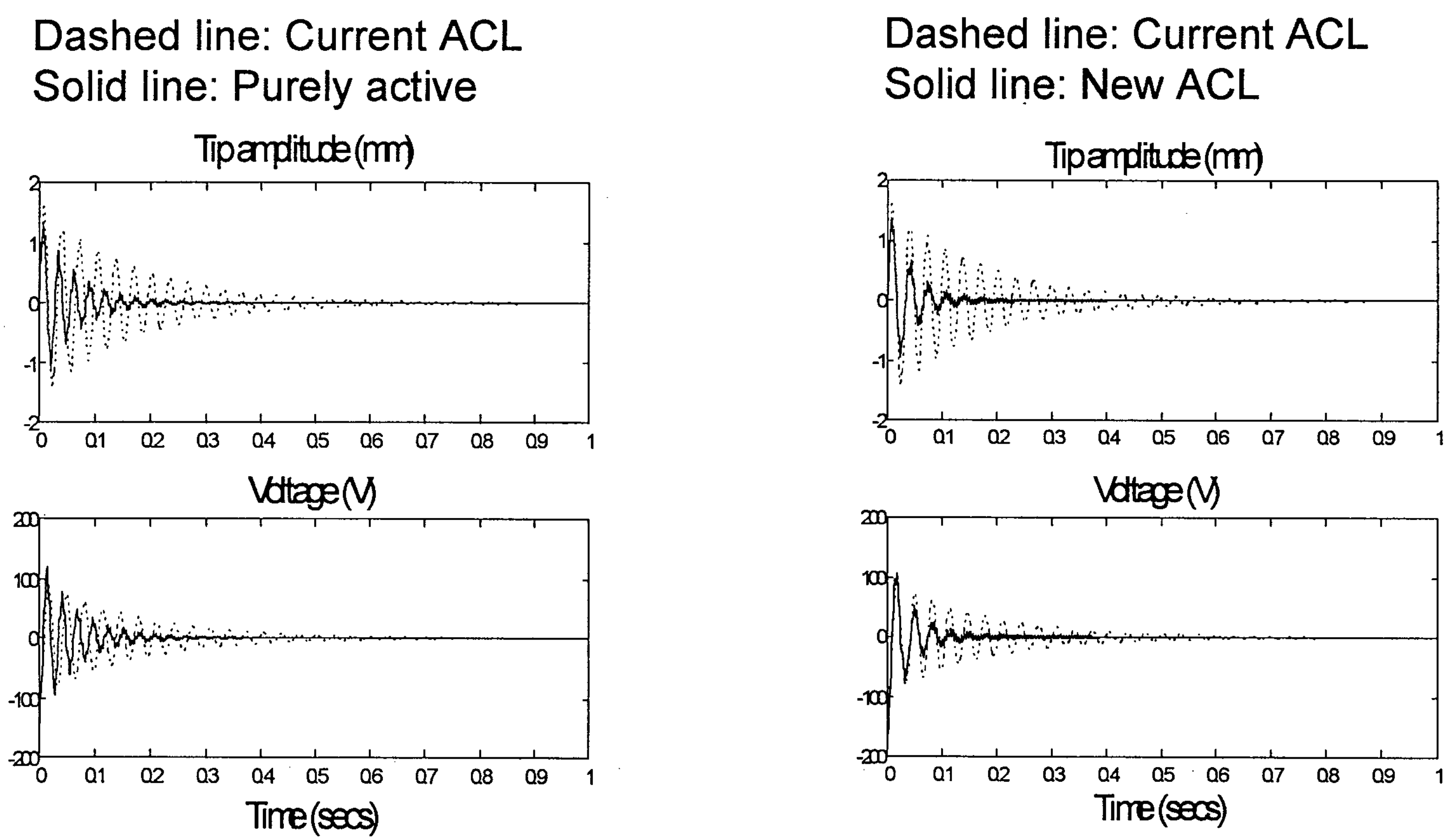


Figure 11. **Structure responses and required voltage. Left plots: solid line - purely active; dashed line - current ACL. Right plots: solid line - new ACL, dashed line - current ACL.**

C. LIST OF PUBLICATIONS

Referred Journal Publications

K.W.Wang, Y.S.Kim and D.B.Shea, "Structural Vibration Control via ER-Fluid-Based Actuators with Adaptive Viscous and Frictional Damping," Journal of Sound and Vibration, 177(2), pp.227-237, 1994.

J.S.Lai and K.W.Wang, "Parametric Control of Structural Vibrations via Adaptable Stiffness Dynamic Absorbers," ASME Journal of Vibration and Acoustics, 118(1), pp.41-47, 1996.

K.W.Wang, J.S.Lai, and W.K.Yu, "An Energy-Based Parametric Control Approach for Structural Vibration Suppression via Semi-Active Piezoelectric Networks," ASME Journal of Vibration and Acoustics, 118(3), pp.505-509, 1996.

W.H.Liao and K.W.Wang, "On the Active-Passive Hybrid Control Actions of Active Constrained Layers," ASME Journal of Vibration and Acoustics , accepted for publication.

W.H.Liao and K.W.Wang, "A New Active Constrained Layer Configuration with Enhanced Boundary Actions," IOP Journal of Smart Materials and Structures, special issue on active/passive damping, accepted for publication.

W.H.Liao and K.W.Wang, "On the Analysis of Viscoelastic Materials for Active Constrained Layer Damping Treatments," Journal of Sound and Vibration, in review.

Conference Proceeding Publications

K.W.Wang, Y.S.Kim, H.S.Lee and Dennis B. Shea, "Vibration Control of Flexible Structures via Electrorheological-Fluid-Based Dampers," Proc. SPIE Conf. on Smart Structures and Materials, vol. 1917, pp.157-167, 1993.

K.W.Wang, W.K.Yu and J.S.Lai, "Parametric Control of Structural Vibrations via Piezoelectric Materials Shunted with Real-Time Adaptive Circuits," Proc. SPIE Conf. on Smart Structures and Materials, vol. 2192, pp.120-131, February 1994.

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K.W.Wang, J.S.Lai, W.K.Yu, "Structural Vibration Controls via Piezoelectric Materials with Real-Time Semi-Active Networks," Proc. of ASME IMCE, AD-45, pp.219-226, November 1994.

W.H. Liao and K.W. Wang, "On the Active-Passive Hybrid Control Actions of Active Constrained Layers," Proc. of the 15th ASME Conf. on Vibration and Noise, DE-84(3), pp.125-141, 1995.

S. Kahn and K.W. Wang, "On the Simultaneous Design of Active-Passive Hybrid Piezoelectric Actions for Structural Vibration Controls," ASME IMCE, November 1995.

W. H. Liao and K. W. Wang, "Analysis and Design of Viscoelastic Materials for Active Constrained Layer Damping Treatments," Proc. SPIE Conf. on Smart Structures and Materials, vol. 2720, pp.212-223, 1996.

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K.W.Wang, "Parametric Control of Structural Vibrations -- Piezoelectric Materials with Real-Time Semi-Active Networks," Wave Motion, Intelligent Structures, and Nonlinear Mechanics, Edited by A. Guran and D. J. Inman, World Scientific Publishing Company, pp. 112-134.

K.W.Wang and S. Kahn, "Active-Passive Hybrid Structural Vibration Controls via Piezoelectric Networks," Structronic Systems, Smart Structures, Devices and Systems, Edited by H.S. Tzou et al., World Scientific Publishing Company, to appear in 1996.

Workshop Abstract Publications

K.W.Wang and J.S.Lai, "Semi-Active Control of Structural Vibrations via Adaptive Materials," First US Army Research Office Smart Structure Workshop, Sept. 1993.

W.H. Liao and K.W. Wang, "On the Active-Passive Hybrid Actions of Structures with Active Constrained Layer Treatments," Second US Army Research Office Smart Structure Workshop, Sept. 1995.

S. Kahn and K.W.Wang, "Structural Vibration Controls via Active-Passive Hybrid Piezotronics," Second US Army Research Office Smart Structure Workshop, Sept. 1995.

D. LIST OF PARTICIPATING PERSONNEL

Principal Investigator: Professor K. W. Wang

Graduate Students employed through this contract:

W. H. Liao: Ph.D. student (expect to graduate by December 1996)
W. K. Yu: M.S. student (graduated 1995)

Graduate Students not employed through this contract but have made direct contributions to the program: J. S. Lai (Ph.D. student graduated 1995), Andy Vavreck (Ph.D. student, expect to graduate by October 1996), Steve Kahn (Ph.D. student), W. Yeung (M.S. student, expect to graduate by August 1996).

REPORT OF INVENTIONS

Penn State Invention Disclosure No. 95-1497, "A New Intelligent Constrained Layer Actuator with Boundary Elements for Active Action Enhancement".